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FABRICATION AND TEST OF A FLUIDIC FUEL-CONTROL AND BLEED-AIR-LO--ETC(U)

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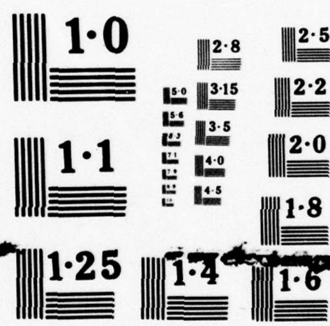
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Bleed Air Load Control System
Auxiliary Power Unit

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This program has produced a production fluidic fuel-control and bleed-air-load-control system which consists of a fuel control, a load valve, and a temperature sensor. Three sets of hardware were produced for use in a follow-on program. This hardware will be subjected to acceptance tests on the AiResearch Model GTCP85-180 gas turbine engine.

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20. Abstract (continued)

The production system improved the steady-state performance over that demonstrated on the prototype control produced under the previous program. The fluidic circuits were designed to perform within specification limits when operated at altitude as well as high and low temperature conditions. Designs and drawings were modified wherever necessary to facilitate production.

The system underwent engine and fuel bench testing to confirm design improvement and performance. As part of this testing, a 50-hour endurance bench test of the fuel control was performed. This test, as well as the engine tests conducted, identified minor problems with the fuel metering valve and the speed sensor which were easily corrected. The appropriate design changes were incorporated into the production configuration.

The production fluidic fuel-control and bleed-air-load-control system performed satisfactorily, meeting the program and engine requirements and is therefore recommended for follow-on program testing.

FOREWORD

This is the final report of a program conducted by AiResearch Manufacturing Company of Arizona, a Division of The Garrett Corporation, for the Department of the Army, Harry Diamond Laboratories. The purpose of the program was to fabricate and test three sets of fluidic fuel-control and air-bleed-load-control systems and to subject one of the systems to a 50-hour endurance bench test.

The program was authorized by the Department of the Army under Contract DAAG39-76-C-0129 and was conducted during the period from July 25, 1976, through August 31, 1977, under AiResearch Master Work Order 3209-779315-61-0100. Mr. John Goto of the Harry Diamond Laboratories, Adelphi, Maryland, and Mr. Robert Ware of the Mobile Equipment Research and Development Command (MERADCOM) administered the program for the U.S. Army.

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ILLUSTRATIONS

1. INTRODUCTION

This report presents the results of a program conducted by AiResearch Manufacturing Company of Arizona, a Division of The Garrett Corporation, to fabricate and test three complete production-type fluidic fuel-control and bleed-air-load-control systems designed for use in gas turbine engine control applications. The system to be fabricated was designed specifically for the AiResearch Model GTCP85-180 gas turbine engine. The program included a 50-hour bench test of one of the fabricated systems.

1.1 Background

As a major manufacturer of gas turbine engines and accessories, AiResearch has maintained an active interest in fluidics for more than 12 years. Research in fluidics, initiated with the intent of applying fluidic control and sensing concepts to AiResearch-manufactured products, has resulted in development of all necessary basic fluidic circuit components, as well as special sensors for control of such parameters as shaft speed, pressure, pressure ratio, temperature, acceleration, angular rate, and position. In addition, AiResearch has developed special photochemical etching and bonding techniques that are used to manufacture completely integrated fluidic control circuits. Fluidic control systems are presently in production for several aerospace applications. These include a speed and torque control system for the thrust reverser on the General Electric CF6 engine on the McDonnell Douglas DC-10 airplane, a ram air pressure regulator on the Lockheed S-3A airplane, and a speed control for the air motor on the Concorde SST thrust reverser and engine nozzle control system.

It has long been recognized that the ability of fluidic circuits to operate in hostile environments makes this technology well suited to fuel control applications on gas turbine engines. Utilizing the available compressor discharge pressure as a control parameter and functional compressor flow as the operating fluid, integral control systems may be designed which do not require external power supplies. In addition, studies pertaining to reliability and cost have revealed considerable advantage for fluidics when compared with other technologies.

In early 1974, USAMERDC awarded AiResearch a contract to develop a fluidic fuel control for a small recuperated gas turbine engine used to provide standby or portable electrical power. Based upon the engine requirements for speed and exhaust temperature regulation, a breadboard fluidic control was fabricated. This control drew heavily upon the technology developed during previous control programs.

Successful completion of the program described above, as well as many other related sensor and transducer development programs at AiResearch, has confirmed the suitability of applying fluidic technology to the control requirements associated with small gas turbine engines. For the most part, however, these programs have dealt with one-of-a-kind applications with subsequent limited exposure to conditions encountered in the field. In addition, the breadboard configuration of these units has not provided information directly applicable to production-type hardware.

To obtain this necessary information, a program was undertaken to fabricate a fluidic fuel control system which could be applied to engines under a variety of operating conditions.

To realize the greatest possible range of field exposure, a fluidic fuel control system was selected that is designed to operate with a gas turbine engine used by all three military services, the AiResearch Series 85 gas turbine. In Navy and Air Force applications, this engine is used to provide electrical and pneumatic power for aircraft main engine starting and support while the plane is on the ground. This engine is used by the Army for generation of electrical power for standby and portable emergency operation in the field. Although these applications require different engine models, the fuel control functions are similar, and direct exchange is possible through recalibration procedures. The specific gas turbine engine chosen for the program was the Model GTCP85-180.

A prototype fluidic fuel control was designed and fabricated to meet the control requirements of the engine specification (AiResearch Model Specification SC-5990B). This unit was bench tested to confirm steady-state performance and engine tested to confirm dynamic response and accuracy.

The program reported herein was formulated as a result of the success of the prototype fluidic fuel control program as described in Report DAAG52-76-C-0012 (AiResearch Report No. 76-411516).

1.2 Statement of Work

The scope of work associated with the acquisition and suitability demonstration of three complete fluidic fuel controls specified for this program was:

Task A - Fabricate and calibrate three complete fluidic fuel control systems. Each system to consist of a fuel control (AiResearch Part No. 710518-1), a temperature sensor (AiResearch Part No. 710552-1), a load valve (AiResearch Part No. 109772-1), a modified electrical speed reset box (AiResearch Part No. 305134-5), and other items required to interface the fuel control system with the engine. Only the fuel control and temperature sensor are considered test units for this program.

Task B - Subject one control system from Task A to an endurance test. This will be a bench test which will run for 50 hours at room temperature. The fuel control system will be cycled through the maximum range of operation during the test. A minimum of 300 cycles will be achieved.

1.3 Program Schedule

Figure 1 presents a bar chart of the program schedule, showing the important program elements and their periods of completion.

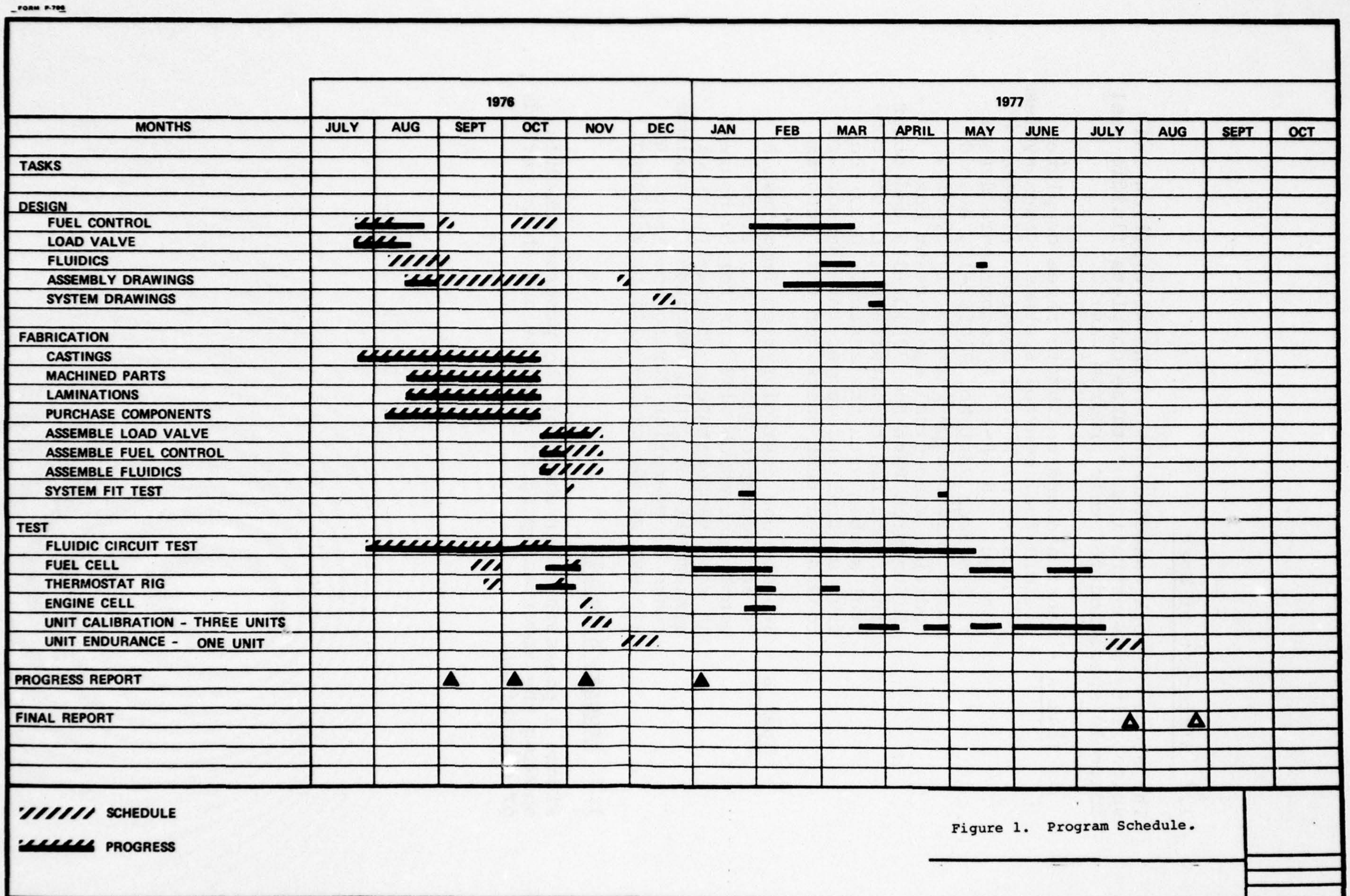


Figure 1. Program Schedule.

2. INVESTIGATION

2.1 Design Improvements

At the completion of the development program, Contract No. DAAG53-76-C-0012, it was evident that a significant improvement in the speed sensor signal was necessary to satisfactorily meet specification requirements of the GTCP85-180 engine. This task along with compensation of the fluidic circuits for ambient altitude and temperature conditions carried into this program. A schematic of the resulting fluidic fuel-control and bleed-air-load-control system is shown in Figure 2.

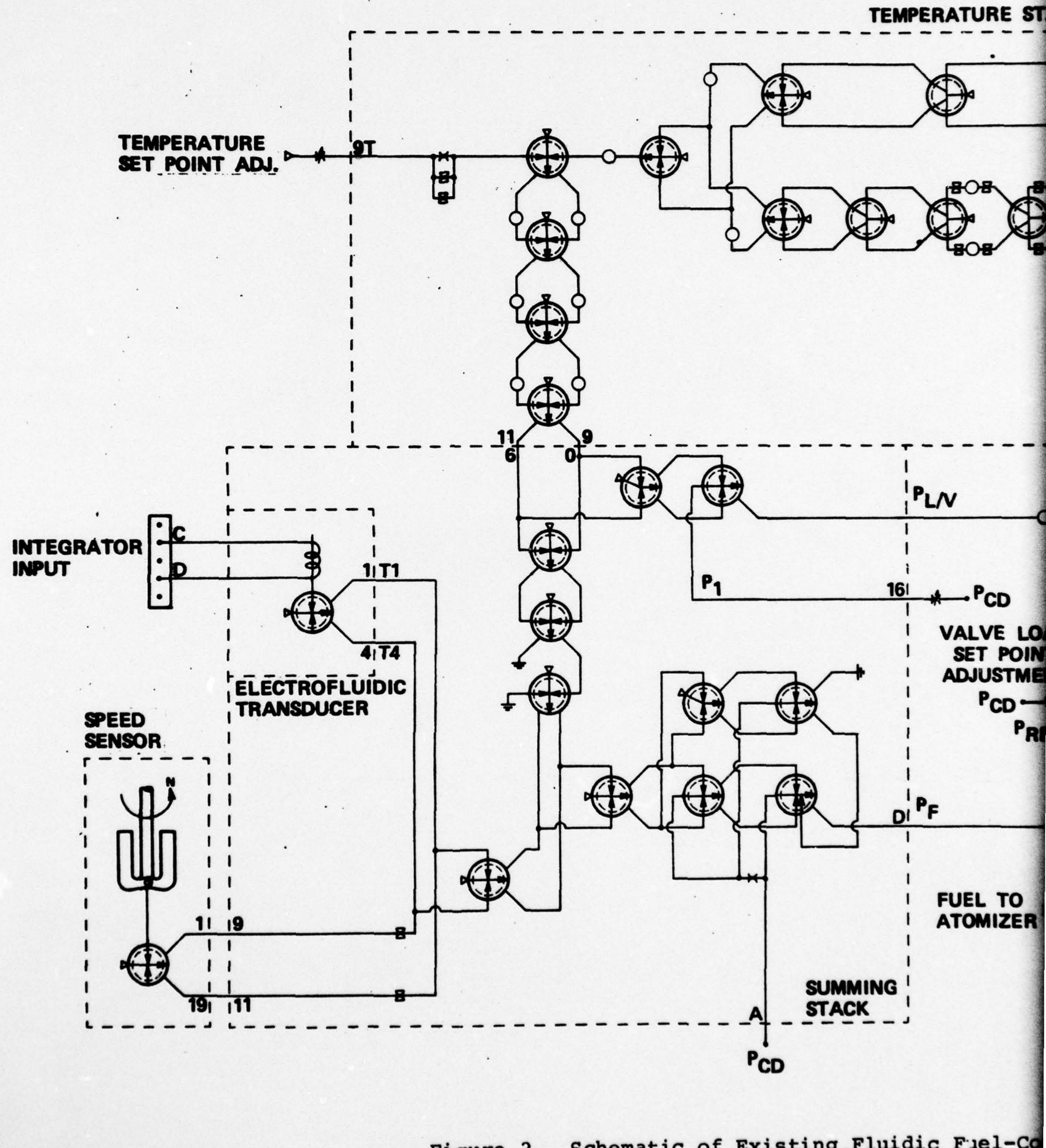
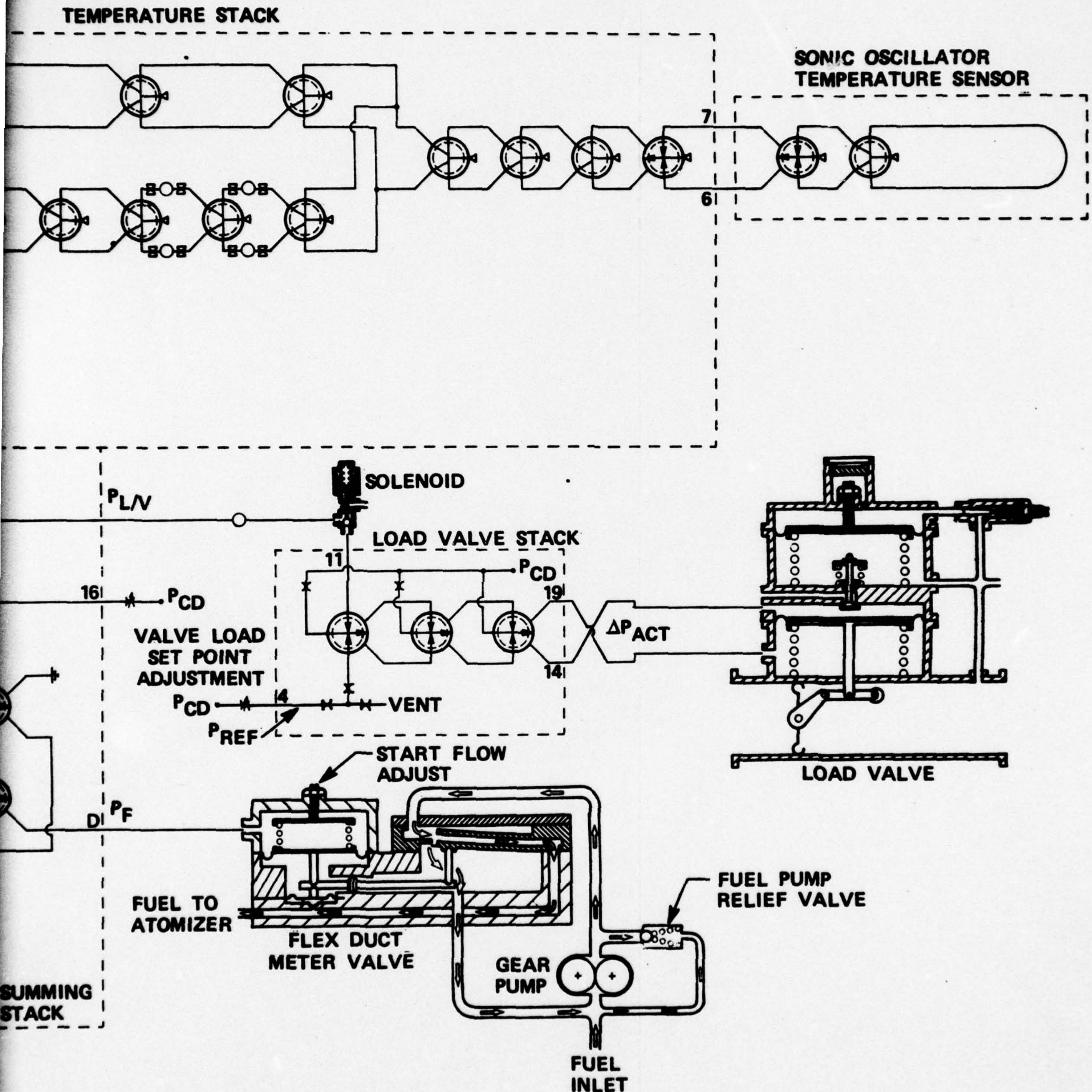


Figure 2. Schematic of Existing Fluidic Fuel-Co



ing Fluidic Fuel-Control and Bleed-Air-Load-Control System.

Speed Sensor.--The problem associated with the speed circuit of the control in the previous program was a low signal-to-noise ratio (S/N). At the completion of the development program, the S/N of the speed circuit using a chopper speed sensor and frequency-to-analog converter was approximately three. An S/N of at least 30 would be required to meet engine specifications.

During the initial stages of this program efforts to significantly improve the frequency-to-analog (F/A) and chopper speed sensor were not successful. Figures 3 and 4 show respectively the circuit schematic and demonstrated performance of the F/A speed circuit used. The best S/N attained was approximately eight.

Other methods of speed sensing were investigated. Those considered were the flyweight speed sensor interfaced with a fluidic pin amplifier, eddie-current drag cup speed sensor interfaced with the fluidic pin amplifier, chopper driven non-linear resonator, and resonant F/A fluidic circuits. Altitude and/or temperature sensitivity restricted the use of all but the flyweight speed sensor.

The flyweight-pin amplifier speed sensor is shown schematically in Figure 5. This sensor utilizes cross-leaf flexural pivots to provide frictionless support of the flyweights and Archimedes-type springs to guide and position the output shaft. The operation of this speed sensor is similar to most flyweight speed sensors in that the force generated by the rotating pivoted weights is balanced by a spring to provide linear displacement as a function of rotational speed. This design transmits the output stroke to a cantilevered pin hanger which utilizes the stroke to position a pin in the interaction region of a fluidic amplifier (pin amplifier). This produces a differential pressure as a function of rotational speed.

The speed sensor has stroke limits which provide saturation control of the pin amplifier output. This allows the output to change with speed only within a speed range which encompasses the engine speed set point. Figure 6 presents the performance of this speed sensor. Figure 7 shows the output of the summing stack, P_F, as a function of speed. Figure 7 also shows the improved S/N ratio. This speed circuit proved to be adequate in meeting engine performance requirements as noted in the discussion of testing.

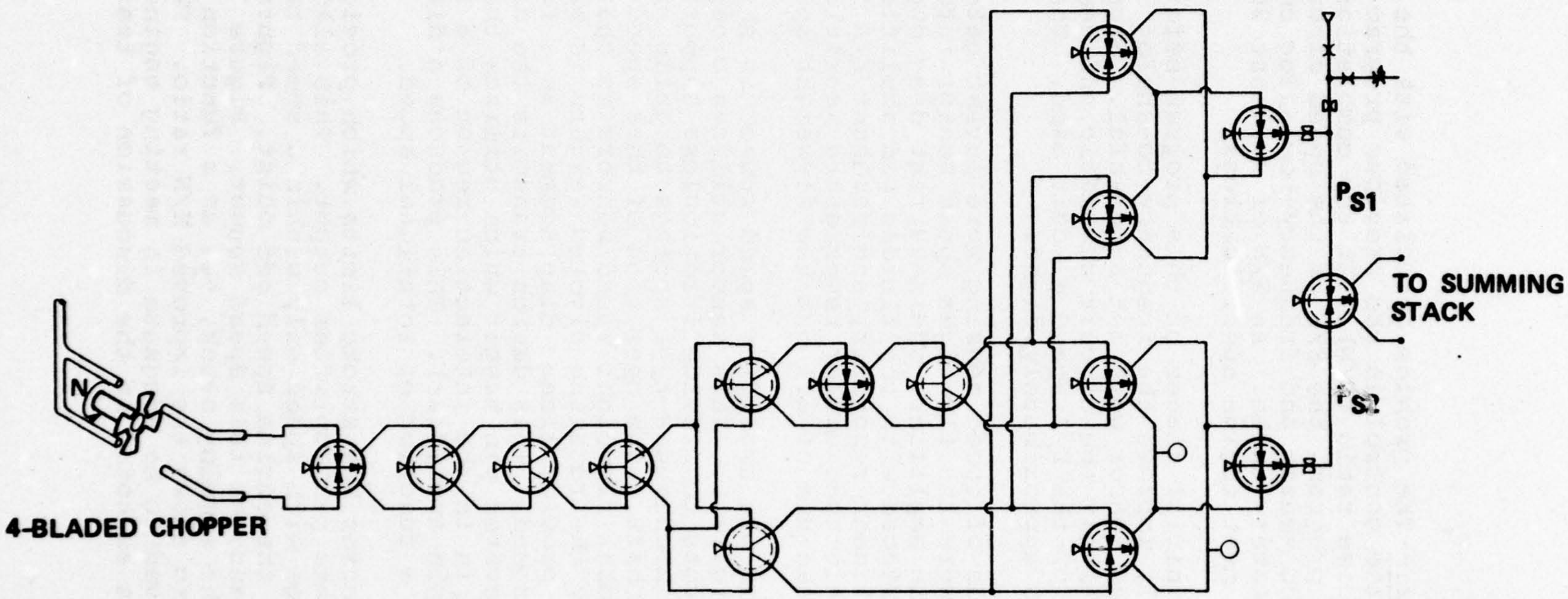


Figure 3. Schematic of Frequency-to-Analog Chopper Speed Sensor.

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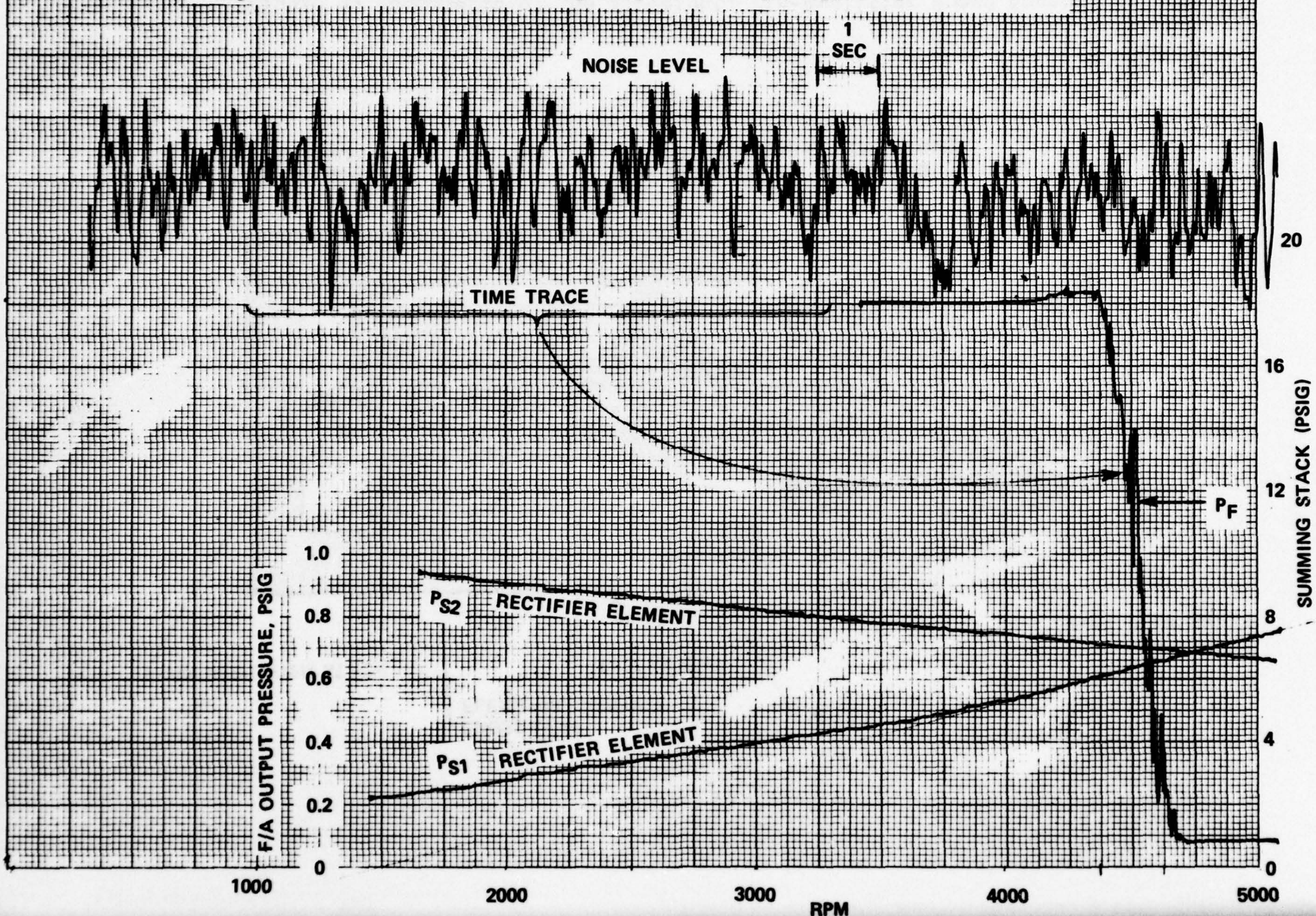
Figure 4. Performance of Frequency-to-Analog Chopper Speed Sensor.



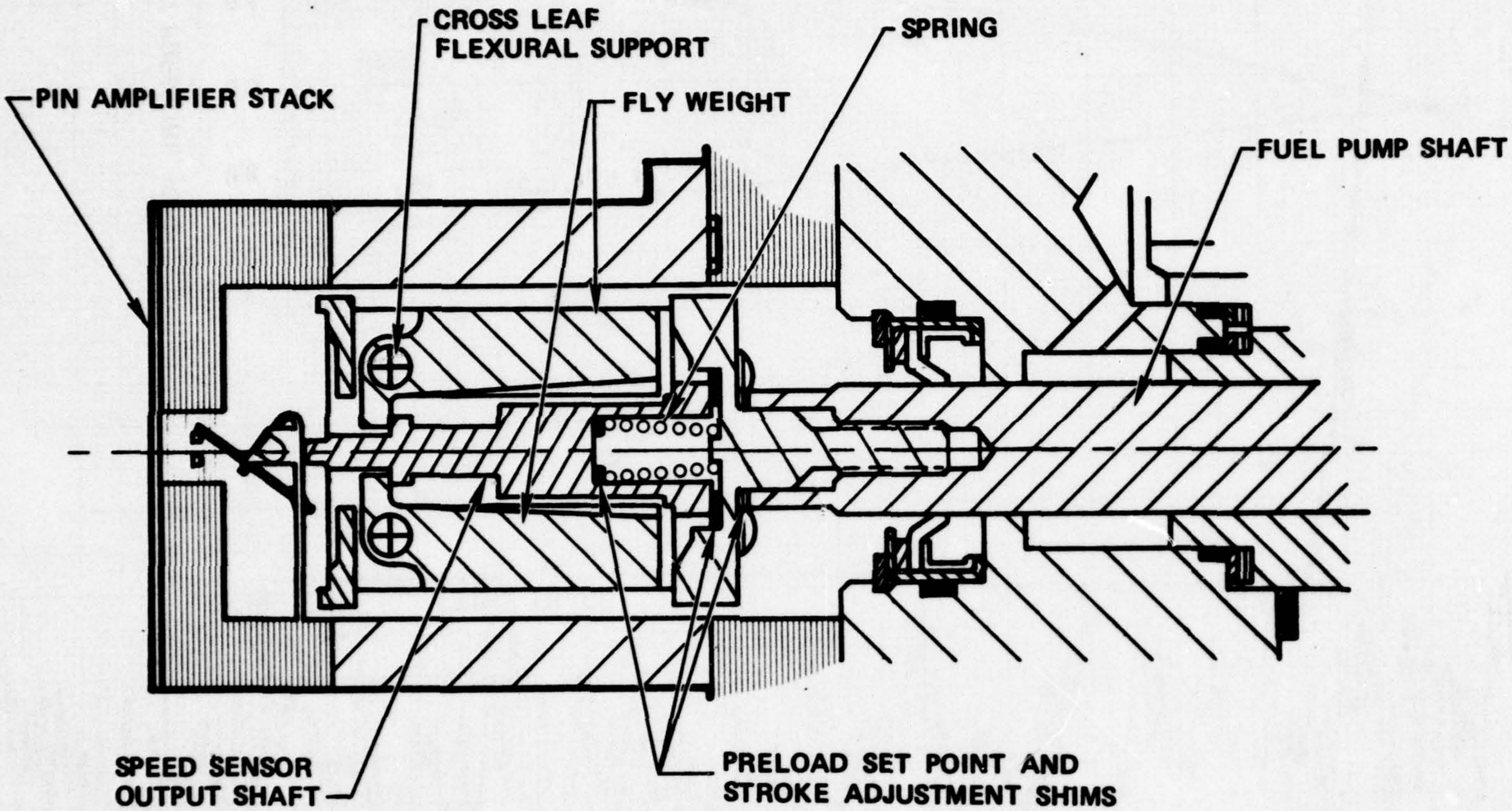


Figure 5. Schematic of the Flyweight, Pin-Amplifier Speed Sensor.

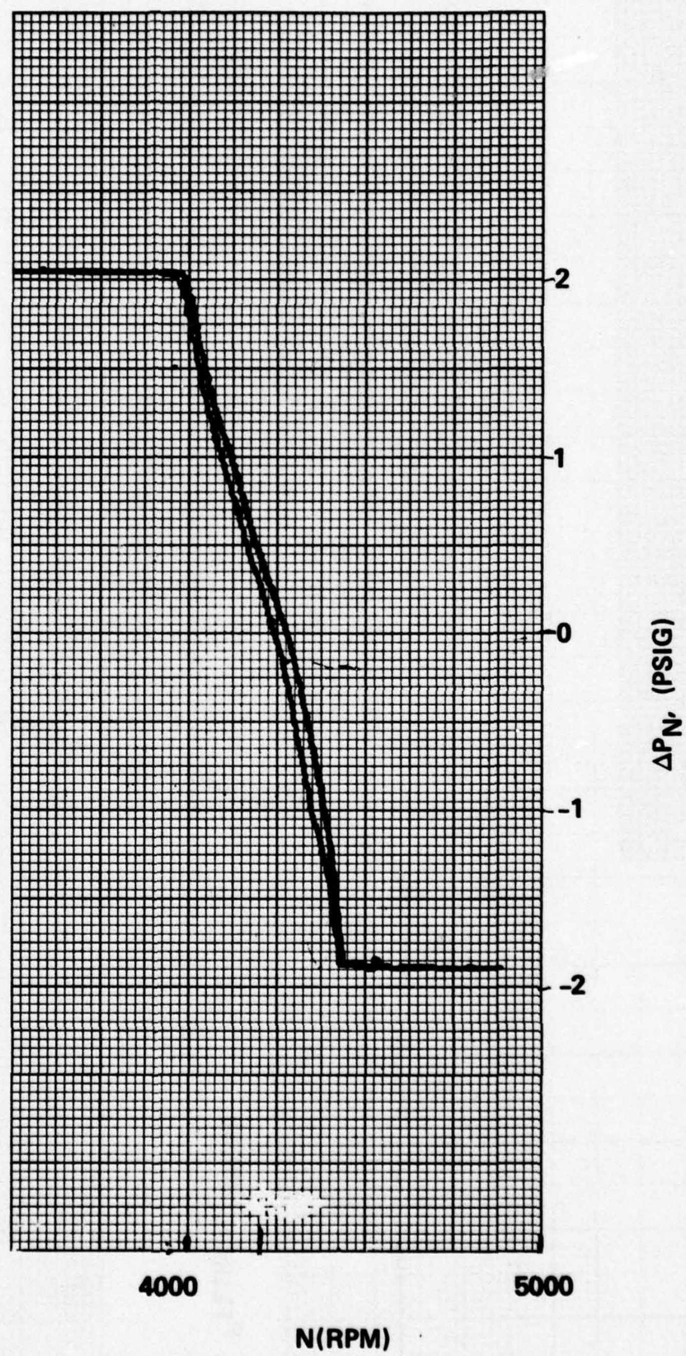
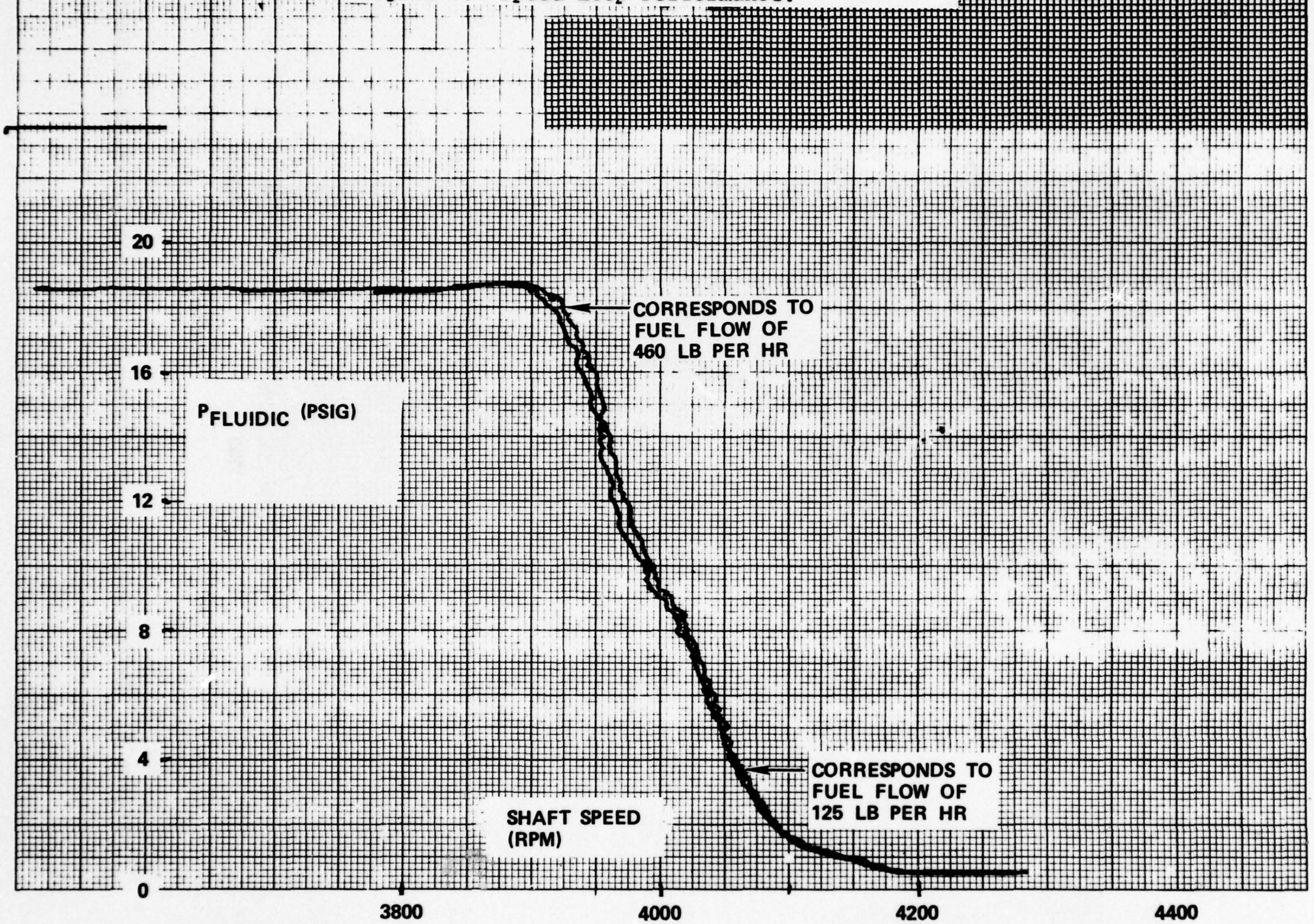


Figure 6. Performance of the Flyweight, Pin-Amplifier Speed Sensor.

Figure 7. Speed Loop Performance.



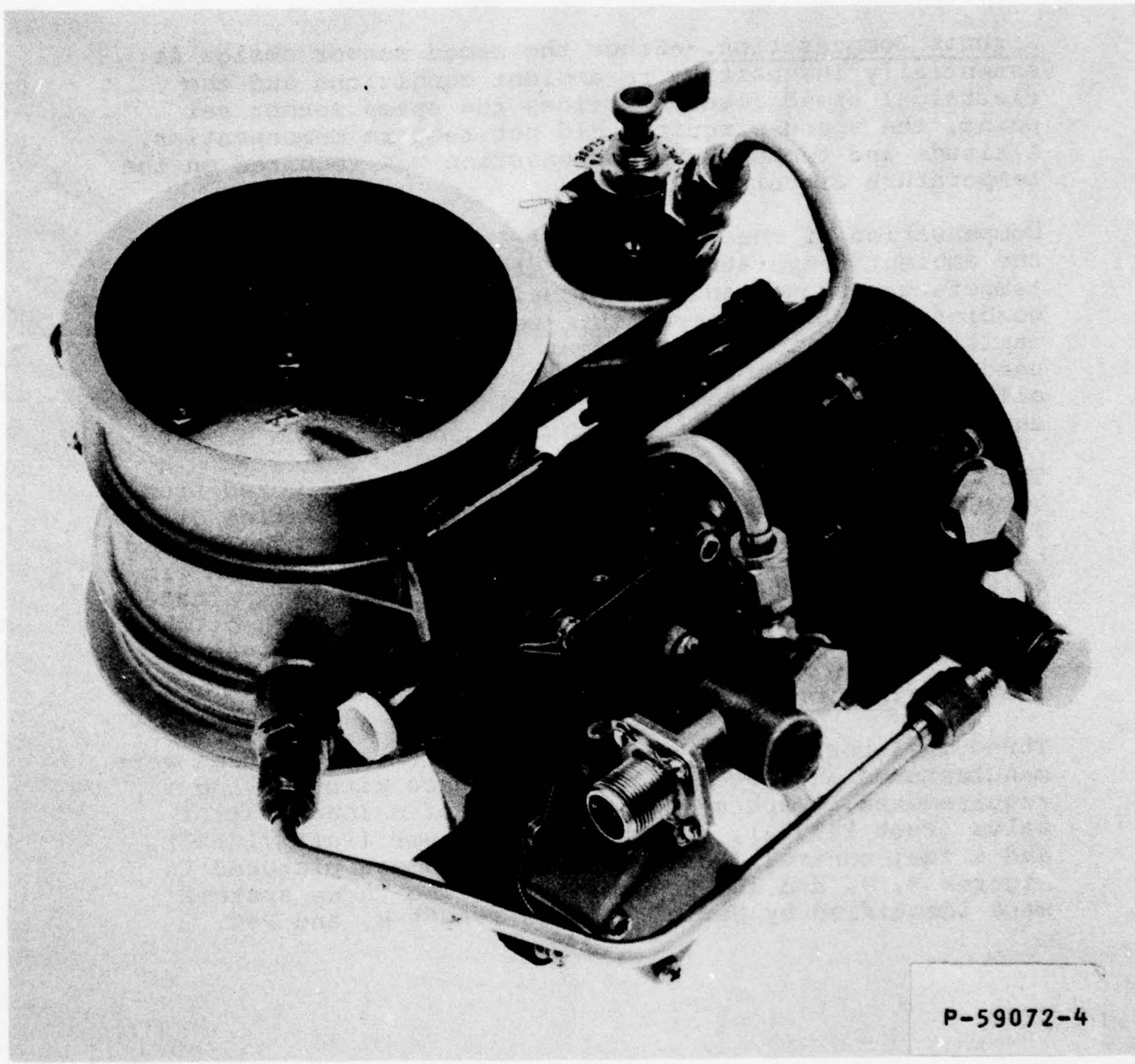
Circuit Compensation.--Since the speed sensor design is essentially insensitive to ambient conditions and the electrical speed reset overrides the speed sensor set point, the speed circuitry did not require compensation. Altitude and temperature compensation was required on the temperature circuits.

Compensation of the temperature circuit involved matching the ambient temperature and altitude sensitivities of the temperature sensor and F/A circuit. The orifice-capillary combination of the temperature set point circuit and capillary-amplifier arrangement in the F/A circuit were used to perform compensation. Compensation was set to allow a variation from the set point of no more than 60 F under the engine-specified ambient conditions.

The frequency of the temperature sensor was lowered from 720 Hz to 630 Hz at 1200 F to simplify compensation of the F/A circuit by operating the F/A circuit in a more linear band. However, this resulted in lowering of the F/A circuit gain by approximately 40 percent, which necessitated the addition of an amplifier in the summing stack of the load valve circuit to compensate for the reduced gain.

2.2 Fabrication

Three fuel-control and bleed-air-load-control systems were manufactured and assembled in accordance with drawing requirements. Each system consisted of a load control valve (Part 109772), a temperature sensor (Part 710552), and a fuel control (Part 710518), which are pictured in Figures 8, 9, and 10, respectively. The three systems were identified by Serial Numbers P-A, P-B, and P-C.



MP-60056 **Figure 8. Load Control Valve, AiResearch Part 109772.**

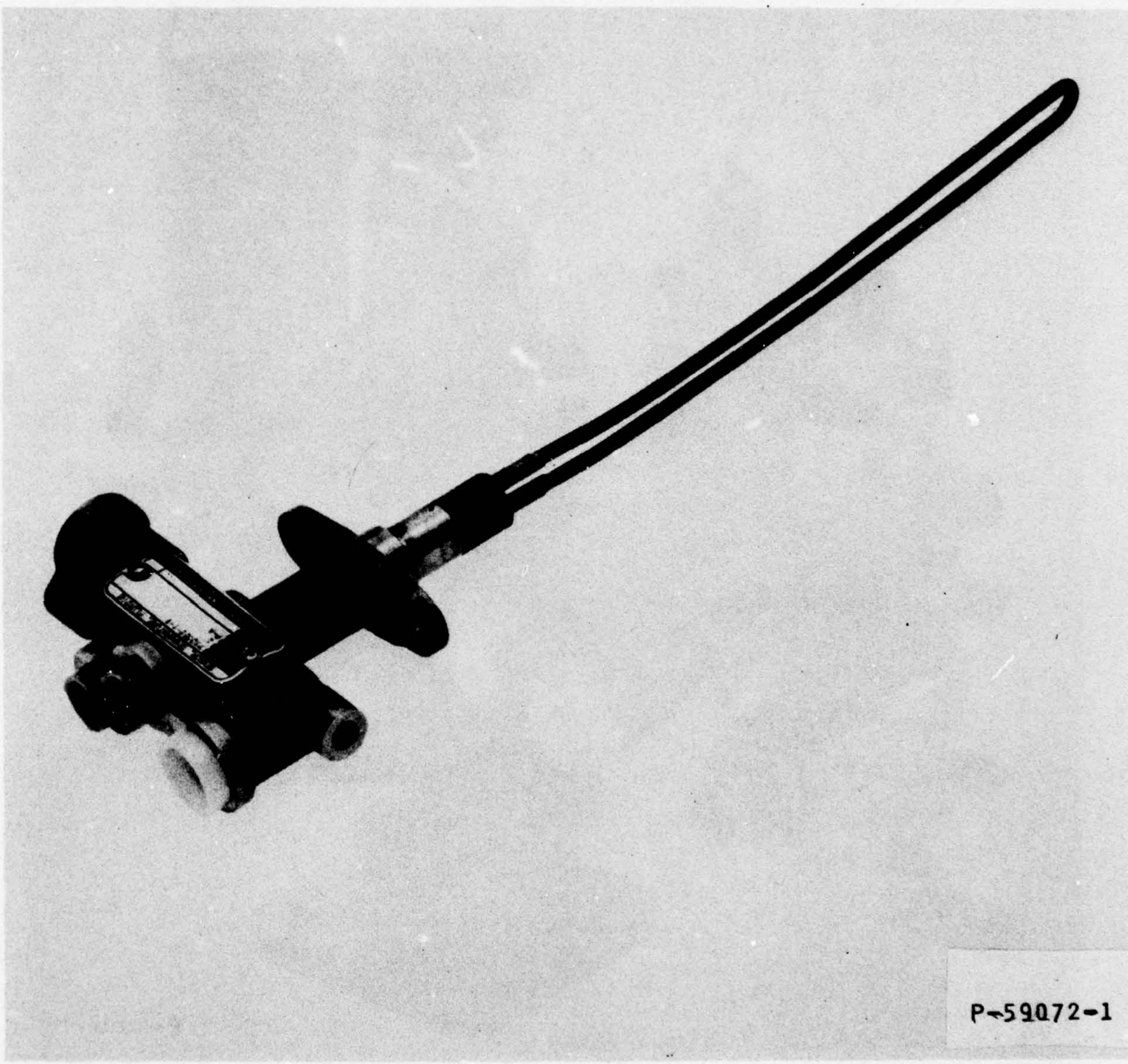
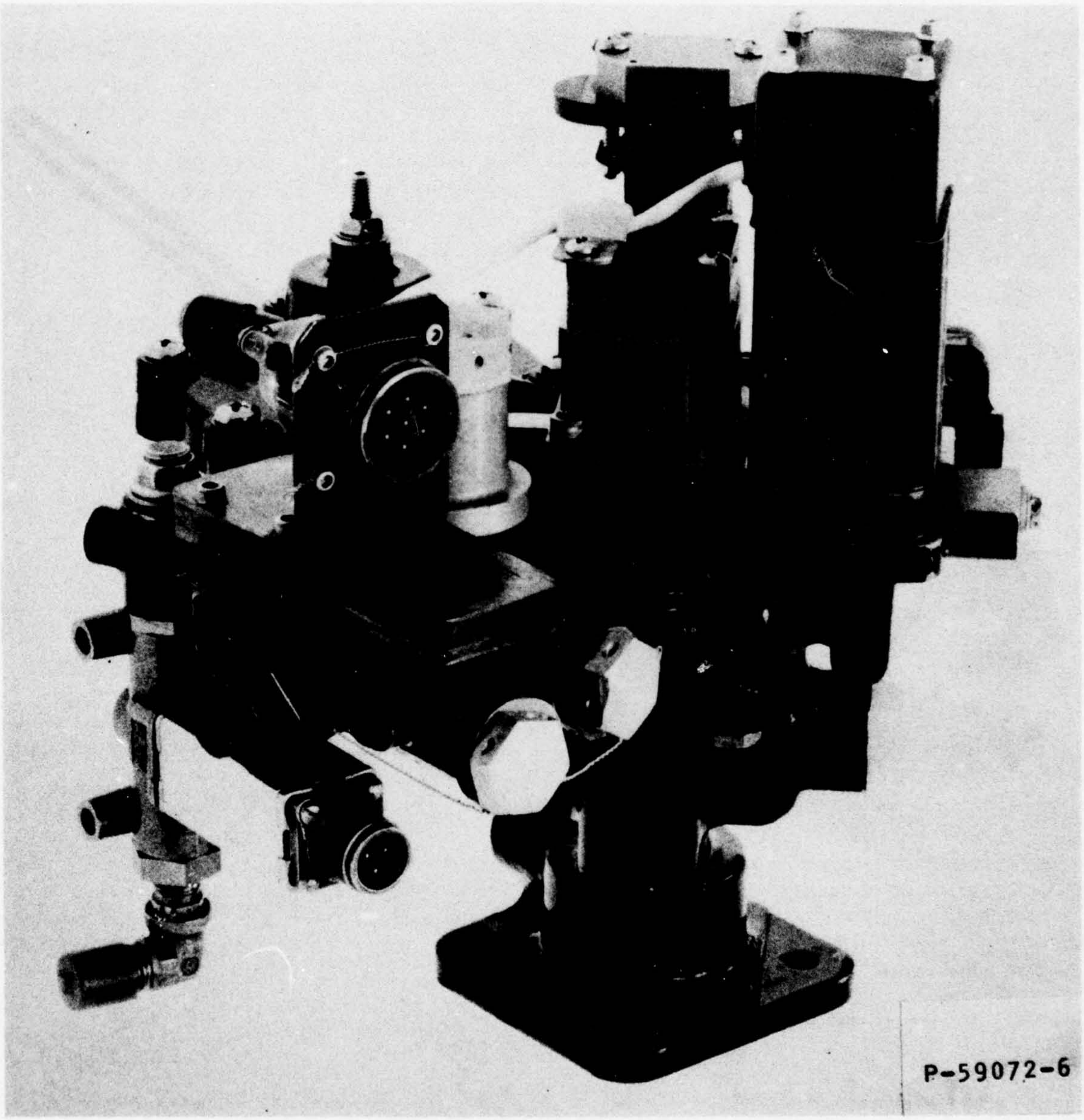


Figure 9. Fluidic Temperature Sensor, AiResearch Part 710552.

MP-60057



MP-60055 Figure 10. Fluidic Fuel Control, AiResearch Part 710518.

2.3 Testing

Each component of each system was tested and met its respective acceptance criteria. These criteria, taken from the production assembly and test instructions for this equipment, are discussed briefly in the following paragraphs.

Temperature Sensor Tests.--Temperature sensors were tested in a thermostat rig at temperatures from 1100 to 1400 F. Gain and set-point frequency were checked for compliance with the following specified limits.

Set-Point Frequency: 630 ±3 Hz at 1200 F

Gain: 0.12 ±0.01 Hz/F

Load Control Valve Tests.--Tests conducted on this item were similar to those required of the load control valves used in nonfluidic systems. The load control valve circuit was tested for proper gain and saturation before installation on the valve. Figure 11 shows the performance of a typical load-control valve circuit. The required performance of the circuit is:

Gain: 25 to 35 with ΔP_{ACT} crossing through zero at $P_{L/V}$ between 3.3 and 3.7 psig with P_{CD} = 35 psig

Saturation: ΔP_{ACT} = 16 ±2 psid with P_{CD} = 35 psig

ΔP_{ACT} = 9 ±1 psid with P_{CD} = 20 psig

With the load valve fully assembled, the adjustment orifice was set to fully close the load valve under operating conditions of $P_{L/V}$ = 3.4 psig. Load valves were subjected to functional tests as well as having the opening rate set according to the specification of the nonfluidic load valve.

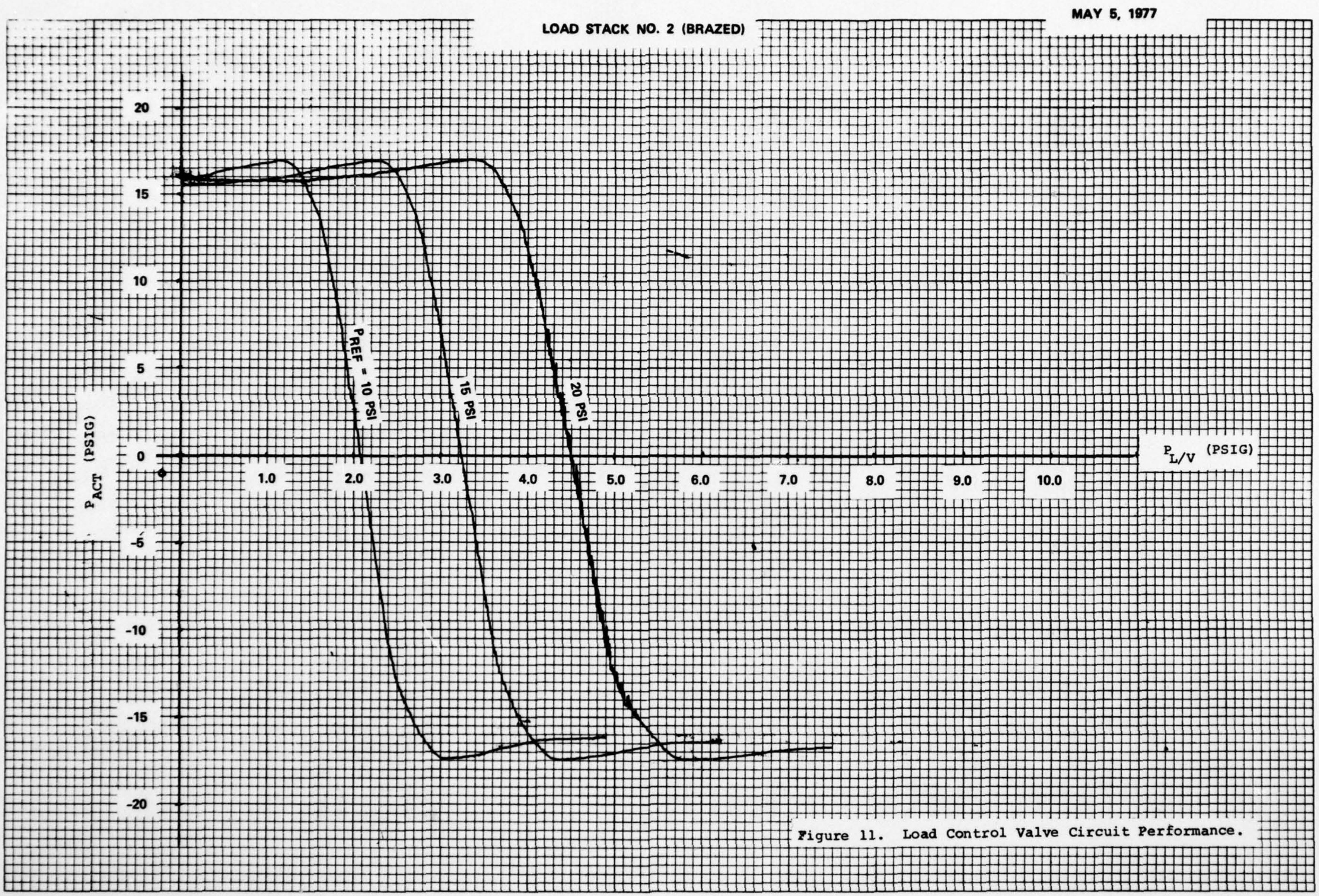


Figure 11. Load Control Valve Circuit Performance.

Fluidic Fuel Control Tests.--The fluidic circuits were tested before they were assembled on the fuel control. After assembly, the fuel control was tested to verify correct hydromechanical operation, calibrated, and then checked for correct gain and set-point performance.

The temperature F/A circuit was tested to demonstrate gain and adjustment orifice control to the following requirements:

Gain: $\frac{\Delta P_{F/A}}{FREQ}$ = 0.014 ±0.002 psi/Hz at frequencies of 550 to 700 Hz

Adjustment Control: Must be capable of adjusting $\Delta P_{F/A}$ between plus 0.5 and minus 0.5 psid at 630 Hz

The speed sensor and pin amplifier were tested to verify gain and set point requirements as follows:

Gain: $\frac{\Delta P_N}{N}$ = 0.008 ±0.001 psi/rpm

Set Point: 4200 ±50 rpm at $\Delta P_N = 0$

Saturation: $\Delta P_N > 1.75$ psi

Figure 6 shows the performance curve of a speed sensor and pin amplifier.

The summing circuit was required to meet the following performance:

Gain: $\frac{P_{L/V}}{\Delta P_{F/A}}$ = 2 ±0.2 with P_1 = 8 psi

$\frac{P_F}{\Delta P_N}$ = 17 ±2 with P_{CD} = 35 psi

$\frac{P_F}{\Delta P_{F/A}}$ = 50 ±5.0 with P_{CD} = 35 psi

= 25 ±2.5 with P_{CD} = 20 psi

Reset Authority: With $\Delta P_N = 0$ and $\Delta P_{F/A} = 0.5$ psid

$P_F > 18.0$ psi at $\Delta P_{RESET} = 1.2$ psid

$P_{CD} = 40$ psig

$P_F < 0.5$ psi at $\Delta P_{RESET} = 1.2$ psid

$P_{CD} = 40$ psig

Performance of the assembled fuel control is shown in Figure 12.

Calibration of the fuel control involved setting the pump relief valve, speed set point, load valve set point, and temperature set point and verifying the electrical reset function and speed droop gain. The requirements were:

Gain: $\frac{W_f}{N} = 2.0 \pm 0.2$ pph/rpm (pump speed)

Speed Set Point: 125 ±2 pph at 4200 rpm (pump speed)

Temperature Set Point: $P_f = 17 \pm 1$ psi at 630 Hz

Load Valve Set Point: $P_{L/V} = 3.4 \pm 0.5$ psi at 630 Hz

Pump Relief Valve: 700 ±15 psig

Reset Control: $\geq$ 400 pph at minus 90 ma $= I_R$, $N = 4200$

$\leq$ 70 pph at plus 90 ma $= I_R$, $N = 4200$

$\leq$ 70 pph at plus 90 ma $= I_R$, $N = 4400$ rpm

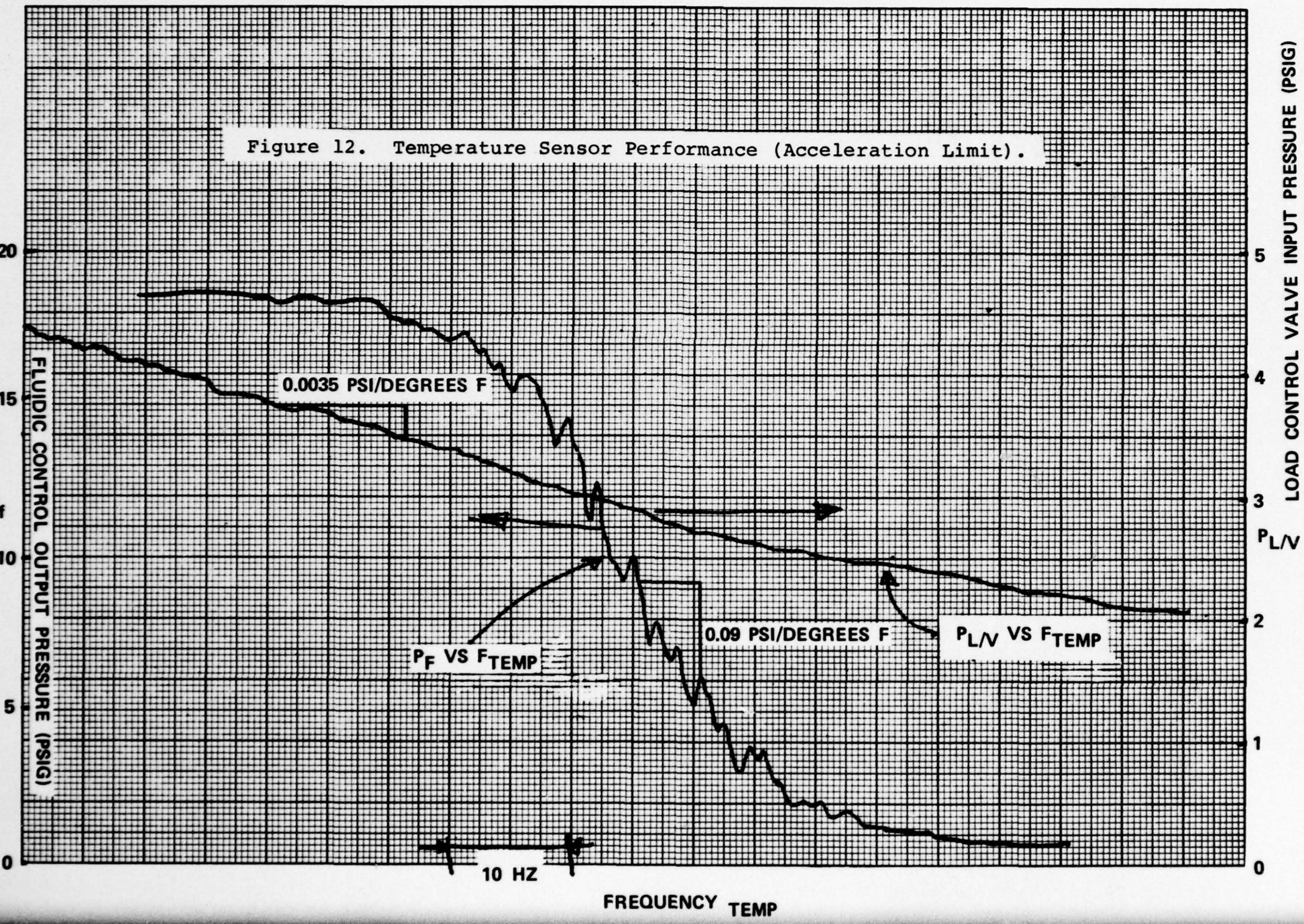


Figure 12. Temperature Sensor Performance (Acceleration Limit).

Engine Tests.--To verify that the design changes incorporated during this program would meet engine performance requirements, engine tests were conducted with the improved fluidic fuel control. Figures 13 and 14 show the engine performance before and after incorporation of the design changes on the fuel control. Figure 14 shows a significant improvement in maintaining speed under no-no-load, loaded, and transient load conditions. The engine specification requires that the fluidic fuel control hold speed within ±0.25 percent under no-load, full shaft load, and full bleed load, within ±2.5 percent during all transients, then recovering to ±0.25 percent within three seconds of initiation of the transient condition. These conditions are indicated on Figure 14.

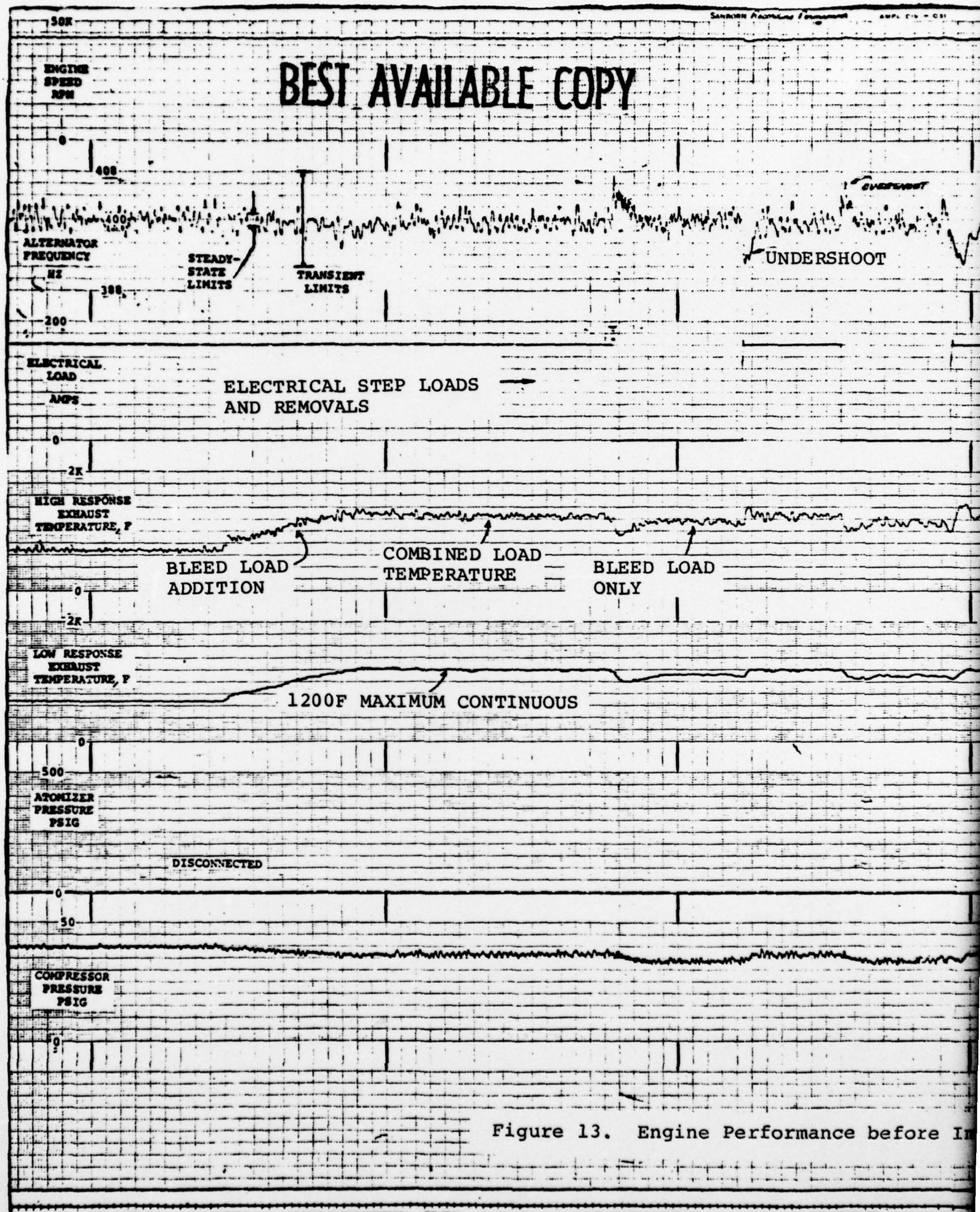
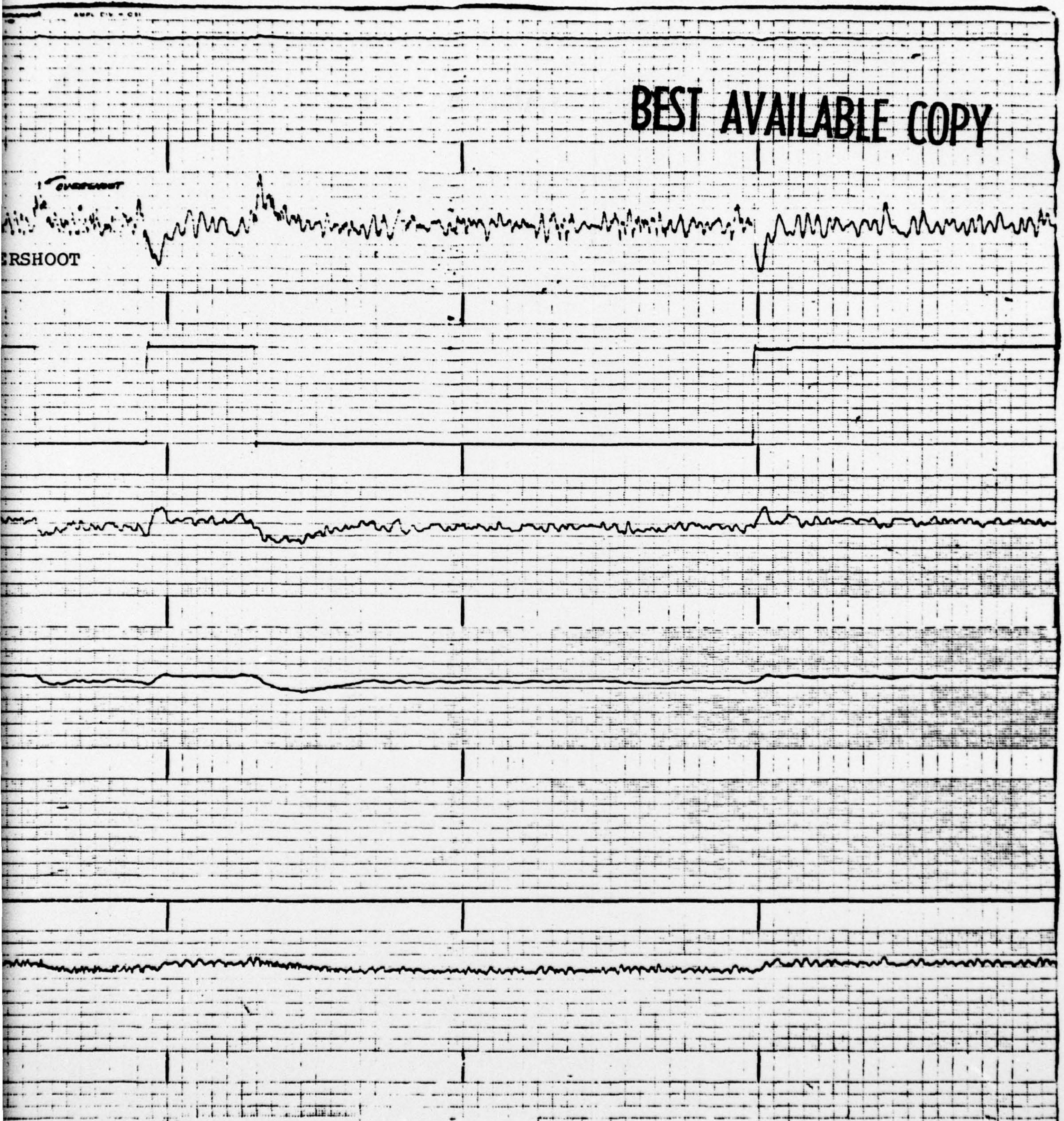


Figure 13. Engine Performance before In



ance before Improvement of the Fluidic Fuel Control.

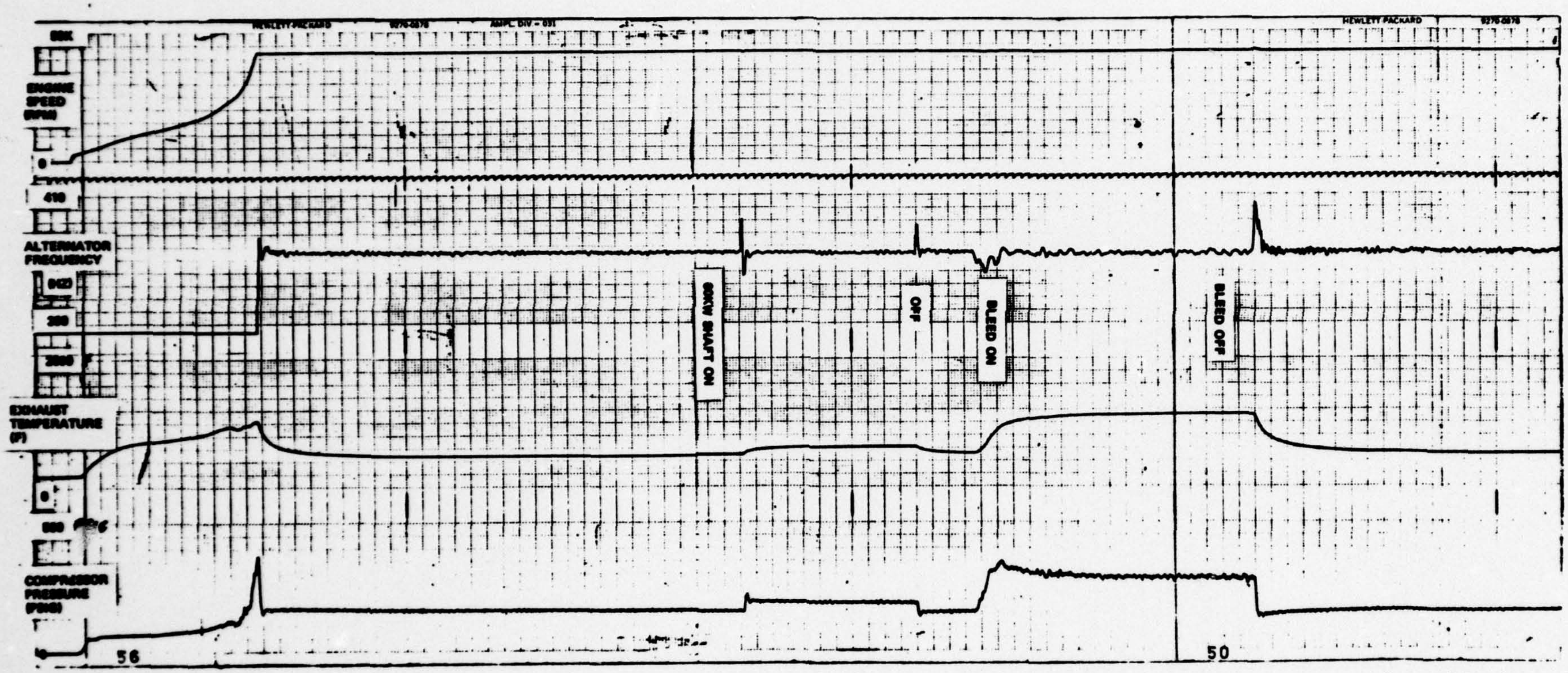


Figure 14. Engine Performance with Improved Fluidic Fuel Control.

2.4 Fuel Control Endurance Bench Test

Fluidic fuel control, Serial P-B, was subjected to a 50-hour, 300-cycle endurance test to isolate and correct any problems in the fuel control design before starting any extensive engine tests.

The fuel control was installed on a fuel control test bench arranged as shown in Figure 15. The endurance unit installed in the test stand is shown in Figure 16. This installation automatically cycled fuel flow through the maximum range of operation every 10 minutes by cycling the current to the electrofludic transducer (electrical reset current). Every half hour the fuel control was automatically shut off and restarted, with the pump speed held at 4200 rpm. Fuel control performance was recorded every two hours.

Eight hours into the endurance test, the maximum fuel flow performance gradually began to deteriorate until at the 23-hour point the test was stopped. Investigation showed the problem to be the flex-duct metering valve. The metering valve was replaced and testing continued. The fuel control with the new flex-duct valve was operated about six hours before the maximum fuel flow performance again started to deteriorate. Testing continued to completion of the planned endurance duration with the remainder of the fuel control components.

Dissection of the failed metering valves disclosed that the 0.010-in.-thick gasket plate of each had ruptured. The rupture, as shown in Figure 17, allowed the atomizer fuel flow to leak to the pump inlet. The leakage caused the flow deterioration observed during the test. This problem has been corrected by increasing the gasket plate thickness to 0.030 inch.

Because deterioration of the maximum flow performance occurred over a period of more than 20 hours, it was possible to observe the remaining performance of the fuel control. The 100-percent speed set point varied by less than one-half percent during testing, minimum flow varied within five pounds per hour, and the fuel flow versus speed gain changed speed less than 10 percent.

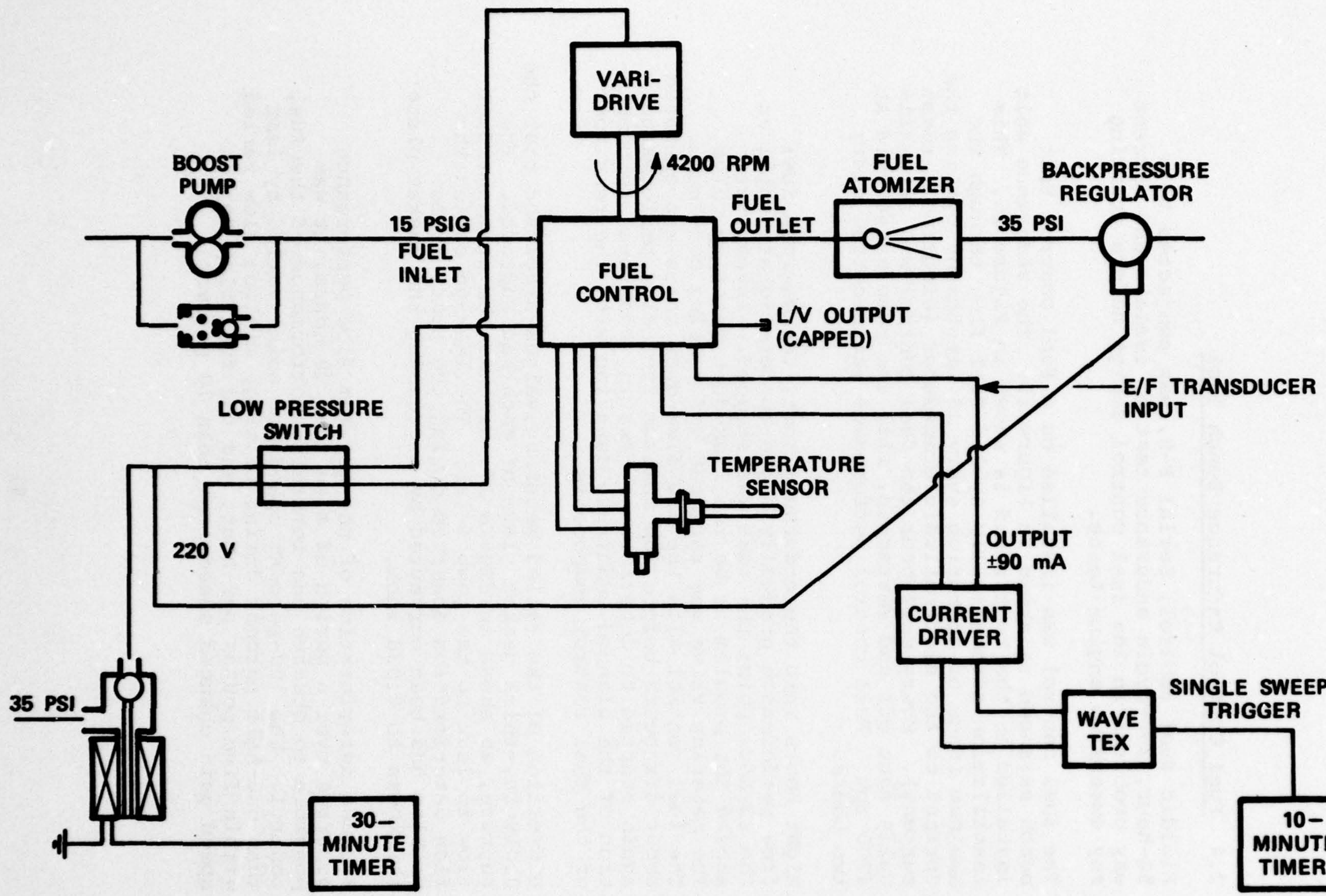


Figure 15. Schematic of Fluidic Fuel Control System.

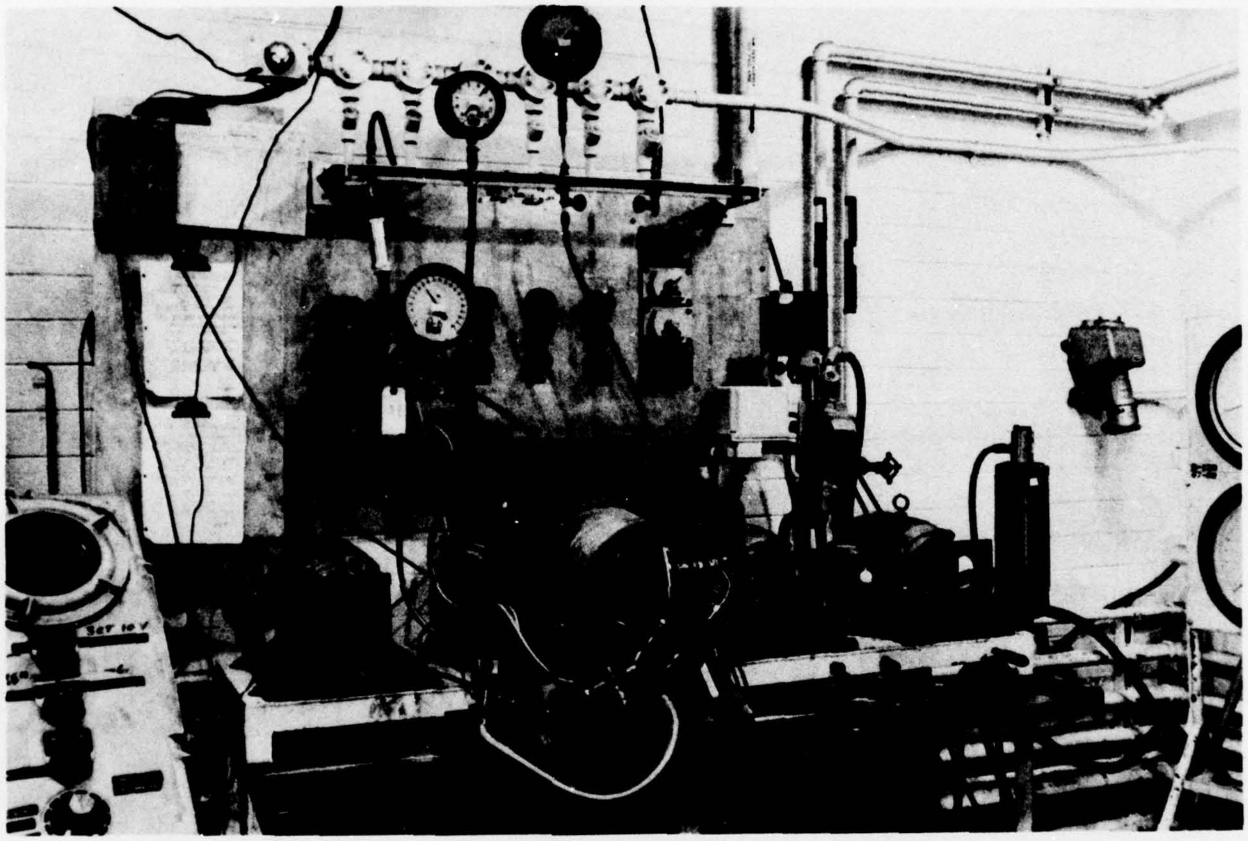


FIGURE 16

TEST INSTALLATION
(FLUIDIC FUEL CONTROL
SERIAL NO. P-B)

Figure 16. Test Installation (Fluidic Fuel Control Serial No. P-B).

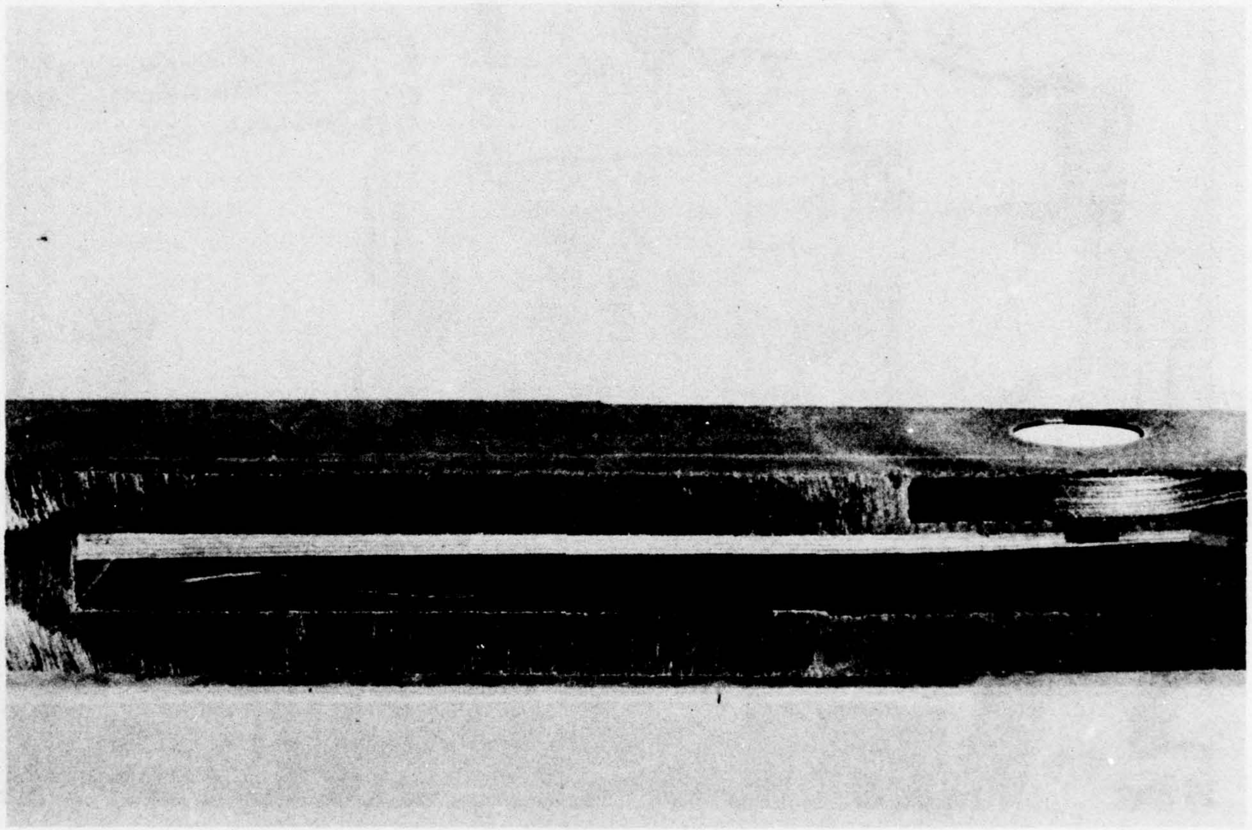


FIGURE 17

CUTAWAY OF METERING VALVE
SHOWING RUPTURE OF GASKET PLATE

Figure 17. Cutaway of Metering Valve Showing Rupture of Gasket Plate.

After the 50-hour endurance test, the fuel control was disassembled to examine components for signs of undue wear or deterioration. The only sign of distress was in the speed sensor flexural support. Sections of the flexure were unsupported, which caused fractures in these sections. This appeared to be due to inadequate filleting of the cross-leaf flexures during bonding. While this condition did not prevent the speed sensor from functioning, it may have caused the variation in set point and gain. The braze material and braze procedure are being changed to insure sufficient braze material to form full fillets on the bonded section of the cross-leaf flexures to correct this problem.

During an engine calibration test with the fluidic fuel control before the 50-hour endurance test, the speed set point shifted lower over a period of time. This caused excessive wear on the speed sensor output shaft and the cantilevered pin hanger of the pin amplifier stack. To correct this problem, a hardened wear pad was added to the pin hanger.

3. CONCLUSIONS AND RECOMMENDATIONS

The development and tests described in this report show that the fluidic fuel-control and bleed-air-load-control system can satisfy the basic control requirements of the GTCP85-180 gas turbine engine. The following specific design goals were met:

1. Controlled fuel scheduling during the engine starting sequence.

2. Engine exhaust gas temperature control through modulation of both the flow of fuel to the engine and extraction of bleed air through the load control valve.

3. Control of engine steady-state speed to within ±0.25 percent of set speed with the electrical fine speed control reset function operating.

Successful completion of this phase of the program leads to the recommendation that the initial objectives of the total program calling for the field evaluation of a substantial number of systems be pursued.

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